Rainfall and Runoff in the Leeward Koolau Mountains, Oahu, Hawaii[1]

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During the course of the investigation of the ground-water resources of southern Oahu, made by the U. S. Geological Survey in cooperation with the State of Hawaii, a water-budget study was used to estimate the quantity of ground water available for development. The effective use of this approach required a detailed knowledge of rainfall and runoff in the area being studied, especially in that part of it lying in the wet Koolau mountains, where most of the ground water is recharged. Past estimates for the rainfall-runoff relationship in this environment were rather speculative, and were based either on extrapolations from areas of lower rainfall or on experience obtained elsewhere. In the present study it became obvious that this relationship would have to be refined.

At the start of the investigation adequate long-term records of rainfall were available for the Schofield plateau and the coastal plain, but records for the rugged central Koolau Range were spotty and not definitive. To alleviate this deficiency, 17 storage rain gages were installed in that part of Kipapa Stream basin that is representative of the high rainfall region of the leeward central part of the Koolau Range (Fig. 1). This part of the basin is covered by an unbroken closed forest.

The gages were made of 5-ft lengths of 3-inch aluminum pipe welded shut at one end. Fourteen of the gages were distributed along the ridge on the south side of the valley (Kipapa Ridge) between the isohyet for an average annual rainfall of approximately 70 inches and the summit of the Koolau Range, and 3 were placed on the floor of the valley over the same distance covered by the first 4 gages on the ridge (see Fig. 1). A tipping bucket recording rain gage with an 8-inch catch was paired with the first of the 3-inch aluminum gages in the valley. The differences in rainfall recorded by the 8-inch gage and measured in the 3-inch gage were insignificant in relation to the amount of rain that fell in the intervals between readings (Mink, 1960).

A recording stream gage was constructed where the stream emerges from the forest, coinciding in location with the first of the rain gages (Fig. 1). Thus two of the variables in the water-budget equation were subjected to close measurement. This paper analyzes the records of rainfall and runoff in the basin for 3 complete calendar years (1957–59). Computations of rainfall and runoff quantities are given in millions of gallons to accord with the terminology usually employed in hydrologic investigations in the Hawaiian Islands.

LOCATION AND DESCRIPTION OF KIPAPA BASIN

The basin of Kipapa Stream is in the central part of leeward Oahu, and, over its full extent, it reaches from the crest of the Koolau Range to the junction of Kipapa Stream with Waikakalaua Stream, which is about 2 miles from Pearl Harbor. Only the long and narrow upper third of the basin was included in the study. This part of the basin is almost 5 miles long, ranges in width from about 2,000 to 7,000 ft, and has a drainage area of 4.3 sq miles. The gaging station on the stream is 700 ft above sea level and the rain gage on the ridge overlooking the stream gage is 1,150 ft above sea level. The widest and highest part of the basin is at its east end, near the crest of the range. The average altitude of this part of the crest bounding the valley is 2,650 ft above sea level, and the highest altitude is 2,785 ft.

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FIG. 1. Map of Kipapa Stream basin showing location of rain gages.

Drainage

The basin of Kipapa Stream, like all the stream basins in the central Koolau Range, is the result of consequent drainage that originally followed a radial pattern on the surface of the Koolau volcanic dome. The present direction of drainage is approximately normal to the northwest trend of the range. The principal drainage pattern in the basin consists of a single channel that extends about one third of the way from the gaging station toward the crest of the range, after which it divides into a main branch and a secondary branch, which extend to a break in slope half a mile from the summit. Near the summit the branches flare out into several smaller watercourses. Throughout the basin small tributaries cascade down the steep sides of the valley into the principal branches. Only the main branch is perennial. The secondary branch has flow during most of the year, but the small tributaries are active only during periods of rainfall. Below the gaging station the flow of the stream is ephemeral.

The main valley is V-shaped in cross-section, and has walls with slopes averaging 25° to 30°. The small tributaries have incised sharp embayments in the steep walls. Over the first 22,000 ft along its longitudinal axis the gradient of the bottom of the valley is about 3°, but about 2,500 ft from the crest the over-all gradient of the basin abruptly increases to approximately 20° and each stream becomes a series of small cascades. Along that part of the stream having the gentle gradient the bottom of the main valley is 100–200 ft wide; in the upper steep part of the basin the valley bottoms are only as wide as the stream channels. The width of the main channel throughout the valley is ordinarily less than 20 ft.

The closed montane forest that covers the drainage basin consists of dense vegetation growing over all but a few of the most precipitous slopes. The typical larger plants include *ohia lehua, koa,* tree fern, false staghorn fern (*uluhe*), guava, and ginger. Near the southwest end of the area groves of eucalyptus trees are common. A mat of vegetation below the larger plants provides an almost complete cover over the soil. The thick vegetation discourages travel within the area except along an established ridge trail and in the stream bed.

Geology

All of Kipapa basin is underlain by basalt and olivine basalt of the Koolau volcanic series. These basalts occur as thin flows of pahoehoe and aa that dip about 5° toward the southwest. Neither dikes nor pyroclastic materials are found in the basin. Measurements taken at vertical sections along the stream show a higher proportion of aa than pahoehoe, but the difference may be based upon a sample too small to be significant. The proportion of aa-clinker could be expected to increase, however, with distance from the rift zone of the Koolau dome from which the lavas effused, which is approximately coincident with the crest of the range.

The rocks of the Koolau volcanic series weather quickly and give rise to soils belonging to the Latasol suborder. Within the Latasol classification are the groups of soils that form through the laterization process. In Hawaii the stages of laterization are determined chiefly by the amount and distribution of rainfall. According to the Soil Survey of Hawaii (Cline et al., 1955), the soils of the mountain section of Kipapa basin are classed generally as Lithosols because of their lack of a genetic profile. However, it is probable that the soils of the wetter portion of the basin are akin to the Hydrol Humic Latasols whereas those nearer the stream gage resemble Humic Latasols. Hydrol Humic Latasols are typical of forest-covered areas with very high rainfall. They are continually wet, and their moisture content accounts for a large proportion of their total weight. The Humic Latasols are less highly weathered and are subject to occasional drying. Both of these soils have high porosity and permeability and are able to hold large amounts of water.

The floor of the valley above the stream channel consists of an irregular terrace, which is underlain by soil intercalated with small lenses of gravel, the whole of which averages from 5 to 8 ft in thickness. The valley walls, except where cliffs occur, are covered by 2 to 3 ft of soil. Small patches of highly weathered talus and large boulders are common in the basin. The stream bed usually consists of deposits of poorly sorted gravel 3 to 5 ft thick, but over short stretches the stream may flow directly on the weathered parent basalt. The mixed gravel contains particles ranging in size from sand to boulders, all of which are moderately to well rounded. Virtually no silt or mud occurs in the stream bed. The smaller pieces of gravel commonly are completely weathered and the larger fragments have a fresh core. Fragments derived from pahoehoe are generally smaller, more rounded and more thoroughly weathered than those from aa.

Heavy, dense vegetation covers the terrace in the valley bottom. The terrace lies about 5 ft above the stream during normal flow, but it is often inundated by high runoff from frequent heavy rains in the narrow valley. During normal flow the stream is free of sediment, and even during flooding it is only slightly turbid. The turbidity probably consists mostly of organic debris and colloidal material from weathered basalt. The stream is in a down-cutting phase, but most of the cutting is due to chemical erosion and little physical erosion is taking place. The thick carpet of vegetation that covers the highly porous soil mantle effectively retards the removal of soil. Also the basalt is highly permeable and can absorb water at a high rate. Occasionally small landslides occur where slippage takes place between the weathered bedrock and the residuum above it, but the sliding material generally is trapped on the slopes, and quickly becomes revegetated. Any of the material from landslides that reaches the stream becomes part of the channel gravel and remains within the drainage basin. However, in the lower part of the basin outside the area of study, where rainfall is less and the land is cultivated, physical erosion is active, and it is this region which provides the sediment that discharges into Pearl Harbor.

RAINFALL

Most of the rain that falls in the Koolau Range is the direct result of either of the two principal atmospheric circulation patterns. The cyclonic pattern associated with low-pressure systems brings storms from which general rains often fall, and the anti-cyclonic pattern associated with high-pressure systems results in orographic rainfall. The precipitation from cyclonic storms is uniformly distributed over wide areas, whereas orographic rainfall is usually restricted to the mountain region. Cyclonic storms are most common during the winter months (November through March), although they occur infrequently during the remainder of the year. Orographic conditions occur throughout the year but are most continuous during the summer period.

The areal distribution pattern of rainfall in the Koolau Range is determined by the orographic component. Orographic rainfall is the result of cooling of trade-wind air as it flows from the northeast over the mountain barrier, which lies approximately normal to the direction of flow of the air mass. The maximum rainfall is about half a mile leeward of the crest of the range. Farther to the southwest it decreases

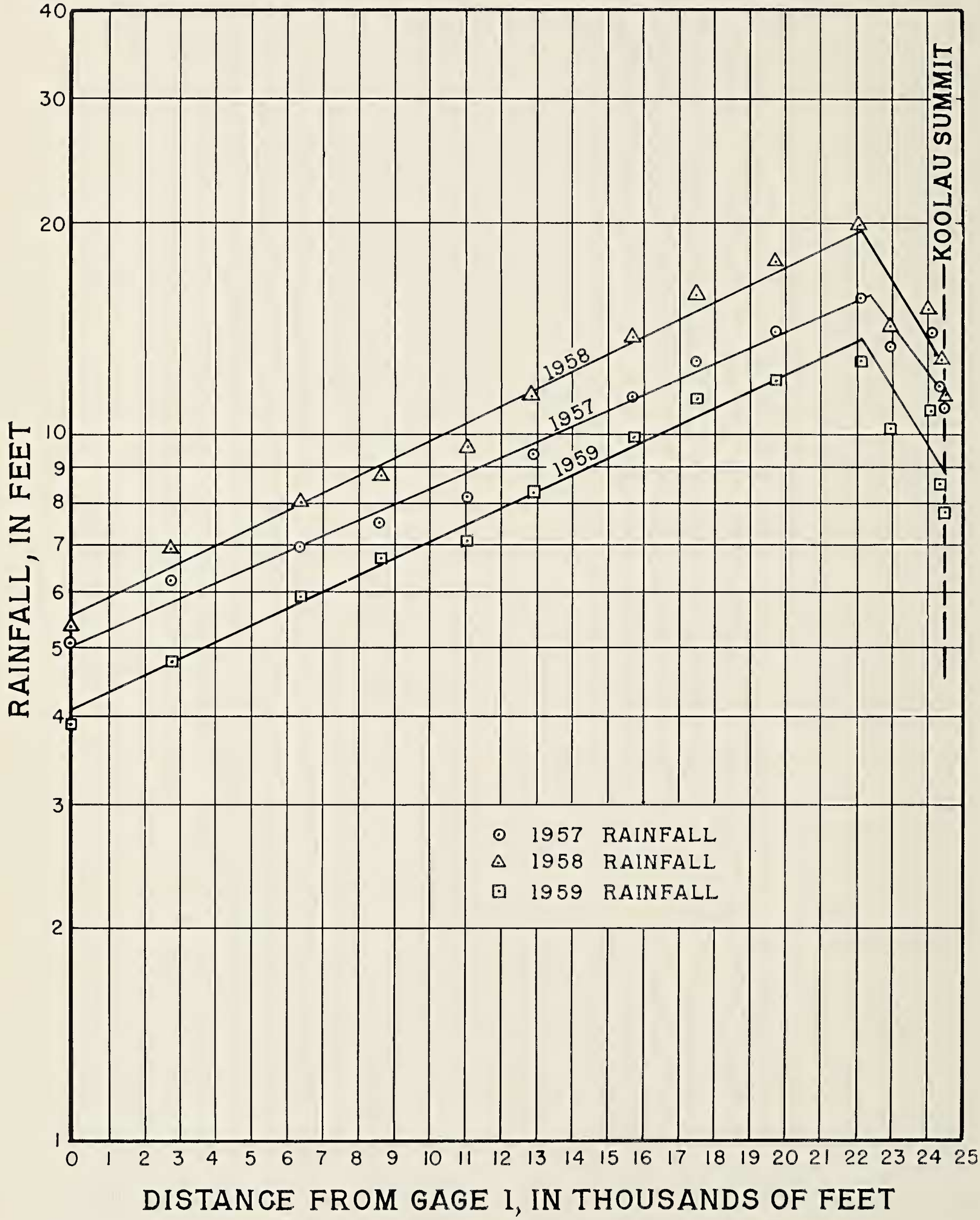

FIG. 2. Rainfall as a function of distance from gage 1 for 1957–59.

TABLE 1

RAINFALL SUMMARY

GAGE	DISTANCE FROM GAGE 1 (ft)	ANNUAL RAINFALL (ft) 1957	1958	1959	1957–59 av.
Ridge					
1	0	5.07	5.37	3.90	4.79
2	2.750	6.20	6.93	4.76	5.97
3	6 400	6.89	8.02	5.87	6.93
4	8,650	7.42	8.79	6.63	7.62
5	11,050	8.17	9.59	7.05	8.27
6	12.900	9.33	11.37	8.28	9.66
7	15,700	11.36	13.72	9.82	11.63
8	17,500	12.69	15.63	11.15	13.16
9	19,730	13.92	17.54	11.88	14.45
10	22,130	15.52	19.87	12.65	16.01
11	23,000	13.38	14.34	10.05	12.59
12	24,100	13.91	15.01	10.78	13.23
13	24.400	11.70	12.71	8.54	10.98
14	24,500	10.58	11.38	7.66	9.88
Valley					
30	0	5.69	6.23	4.14	5.36
33	6,500	7.92	8.80	6.24	7.66
34	8,800	9.13	10.17	7.55	8.95

according to a geometric regression. The point of maximum rainfall apparently coincides very closely with the location of rain gage 10 (Fig. 1). Because cyclonic rains have general uniform areal distribution, they increase the total amount of rainfall over an extended period during which orographic rains may also occur but do not alter the distribution pattern (Mink, 1960).

Early in the investigation it became obvious that the decrease in rainfall in the leeward direction from the point of maximum fall follows the simple decay expression:

$$y = ke^{-ax}$$

where y is the rainfall at any distance, x, from the point of maximum fall; k is the rainfall at the maximum; a is a constant of decrement; and e is equal to 2.7128. By referring the origin to gage 1 for ease of handling in volumetric computations, the rainfall may be considered to increase toward the point of maximum fall, and the equation then becomes:

$$y = ke^{ax}$$

where y is the rainfall at any distance, x, from gage 1, k is the rainfall at gage 1, a is a constant of increment; and e is equal to 2.7128. The effect of cyclonic rain on this equation would be to increase the value of k. Between the point of maximum fall and the crest of the Koolau Range the rainfall appears to decrease geometrically, but the relationship is considerably less perfect than that of the increase from gage 1 (Mink, 1960).

Figure 2 gives plots on semilogarithmic paper of rainfall on Kipapa ridge as a function of distance from gage 1 to gage 14, which is on the Koolau summit, during the years 1957–59. The linear relationships are drawn to accord with regression equations derived by the least squares method. These equations and the equation for the 3-year average are given in Table 2 with pertinent statistical parameters. In all cases the parameters suggest that the equations are highly reliable. A significance test of each of the correlation coefficients shows that it is unlikely that the correlation is a matter of chance. The Sy (standard error of estimate) values fall very close to the line of regression for each of the 3 years and for the 3-year average. In terms of deviation in rainfall at any given point on the line of regression the Sy values are 1.8% for 1957, 7.5% for 1958, 3.9% for 1959, and 4.5% for the 3-year average.

Rainfall on the valley floor is somewhat higher than on the ridge above it on which gages 1–14 are located (see Table 1). The 3 gages on the valley floor cover the same distance relative to the crest as the first 4 gages on the ridge (Fig. 1). Gage 30 lies opposite gage 1, gage 33 is opposite gage 3, and gage 34 is opposite gage 4. Gages on the valley floor cover only the lower third of the distance covered by gages on the ridge, but the plot of their rainfall as a function of distance toward the crest parallels the relationship obtained on the ridge. Assuming that this parallelism holds all the way to the point of maximum rainfall, which approximately coincides with the break in slope, then only the value of k in the rainfall equations as determined for the ridge would be affected.

The 3-year period covered here was, overall, considerably drier than would be expected on the basis of long-term averages obtained elsewhere in the Koolau Range. The year 1957 was moderately dry, having about 20% less rainfall than normal in the wet mountains; 1958 was nearly normal but only because of heavy summer rains; and 1959 was extraordinarily dry, having about 35% less rainfall than normal in the wet mountains. However, the absolute quantities of rainfall have no significant effect on the relative variations in rainfall as expressed in the equations.

Use of the transformed regression equations (see Table 2) enables simple and accurate calculations of the volume of rainfall in the basin. The volume of rainfall is obtained by taking the product of the area under the rainfall-distance curve for the portion of the basin subject to the curve and the width of the basin as follows:

$$V = z \int_{0}^{x_n} ke^{ax} dx$$

where V is the volume of rainfall, z is the width of the basin, and x_n is the distance between gage 1 and the point of maximum rainfall, which is taken to be at gage 10. However, because the outline of the basin is irregular, no single average width is applicable. Therefore, to assure accurate computations, the basin between gage 1 and gage 10 was divided into 22 strips, each of which covered 1,000 ft along the axis of the valley. The distance across the basin measured at the midpoint of each strip then became the width of the basin for that particular strip. The volume of rainfall could then be calculated as follows:

$$V = z_1 \int_{0}^{x_1} ke^{ax} dx + z_2 \int_{x_1}^{x_2} ke^{ax} dx + \ldots z_{22} \int_{x_{21}}^{x_{22}} ke^{ax} dx$$

where V is the volume of rainfall and z is the width of the basin for each strip. The volume computed by this method for 1957 fell within 3.5% of the volume determined by careful planimetry of an isohyetal map whose spacings of isohyets conformed with the equation. The value of k in all the computations was taken as the mean between the rainfall at gage 1 and gage 30 in the valley below.

For the region between the maximum rainfall and the crest of the range the average rainfall was used in volume computations because

TABLE 2

Rainfall Regression Equations for Kipapa Ridge, Annual Basis

PERIOD	REGRESSION EQUATION*	COEFFICIENT OF CORRELATION (r)	STANDARD ERROR OF ESTIMATE (Sy) (log units)	TRANSFORMED REGRESSION EQUATIONS*
1957	$\log_{10}y = .0221x + .7000$	.9987	.0078	$y = 5.01\ e^{.0509x}$
1958	$\log_{10}y = .0255x + .7346$	.9847	.0313	$y = 5.43\ e^{.0586x}$
1959	$\log_{10}y = .0237x + .6073$	.9950	.0165	$y = 4.05\ e^{.0546x}$
1957–59 (average)	$\log_{10}y = .0235x + .6886$	.9933	.0190	$y = 4.88\ e^{.0541x}$

* y = rainfall (ft); x = distance (ft) from gage 1 toward summit.

of the imperfect regression relationship. The volume thus computed for 1957 nearly equaled the volume determined by planimetry.

Rainfall volumes for selected periods other than annual were obtained similarly when the rainfall included an orographic component. The equations for these periods were graphically derived, however, rather than by the method of least squares. These equations are believed to be sufficiently accurate to give significant results. For periods during which only cyclonic rains fell, volumes were computed by taking the average rainfall for the basin, because cyclonic rainfall is uniformly distributed. Two such periods were selected for analysis. For each of these periods the total average catch amounted to somewhat more than 14 inches, and for each period the difference in catch among the gages was less than 10%.

STREAM FLOW

Kipapa Stream has a perennial flow at the gaging station near Wahiawa, although the minimum flow is only a few thousand gallons per day. The part of the basin above the station lies far above the basal water table, which is about 25 ft above sea level in the Pearl Harbor region. It also lies southwest of the high-level ground water in the dike complex, so that virtually all stream flow derives either from immediate rainfall or from rainfall stored temporarily in the porous soil and vegetative mantle. A very small part of the stream flow may be water discharging from small, perched aquifers on local impermeable layers in the basalt. Aside from information obtained from field observations on the movement of water in the basin, evidence of the relationship between stream water, rainfall, and soil water is apparent also from the chemistry of each of these waters.

Figure 3 is a plot of specific conductance as a function of chloride for Kipapa Stream water, rainfall, soil water, stream water flowing from dike compartments in the Koolau Range, and water from tunnels penetrating into Koolau dike compartments. The plots show that at similar chloride concentrations the dike stream and tunnel waters have the highest conductances, suggesting that they have a higher burden of dissolved solids acquired during a longer period of contact with the restraining environment. The plots also illustrate a close relationship between Kipapa Stream water, rainfall, and soil water, as distinct from the relationship between the dike stream and tunnel water. Such relationships may be useful in determining whether other mountain streams whose sources of water are unknown have a significant dike-water component. The fact that virtually all the flow of Kipapa Stream derives immediately from rainfall and soil water within the basin precludes uncertainties in analysis that would arise if water moving to the stream from outside the basin were a component in the streamflow.

Kipapa Stream is "flashy" and responds quickly to rainfall. Figure 4, which is a flow-duration curve for the stream at the gaging station, illustrates the highly variable flow characteristics of the stream. The curve is based on flow records for the 3 calendar years, 1957–59. Although this period was drier than normal, the curve clearly indicates the wide range of flows expectable for the stream. The central measures of tendency and the maximum and minimum daily flow for each of the calendar years and the 3-year average are given in Table 3.

The relatively rapid return of the stream to base flow following rainfall is suggested by the flow-decay curves in Figure 5. These curves represent the cumulative per cent of the measured daily runoff plotted as a function of days after isolated storms that were restricted to about a 1-day period. Prior to each isolated storm the flow of the stream was at base level, and after each storm no rain fell in the basin during the interval of decay. The curves indicate that more than 99% of runoff traceable to each storm occurs within 10 days after the storm. No significant difference in decay time was apparent between orographic rains and cyclonic storms.

Miscellaneous flow measurements made with a current meter in Kipapa Stream from a point about a mile downstream from the gaging station to the fork in the stream at rain gage 34 during low-flow periods provided the interesting, and unexpected, conclusion that the stream acts as either a gaining or a losing stream, depending upon antecedent rainfall conditions in the basin. For periods preceded by moderate to high rainfall it continually gains from the fork to about ½ mile below the gaging station, prob-

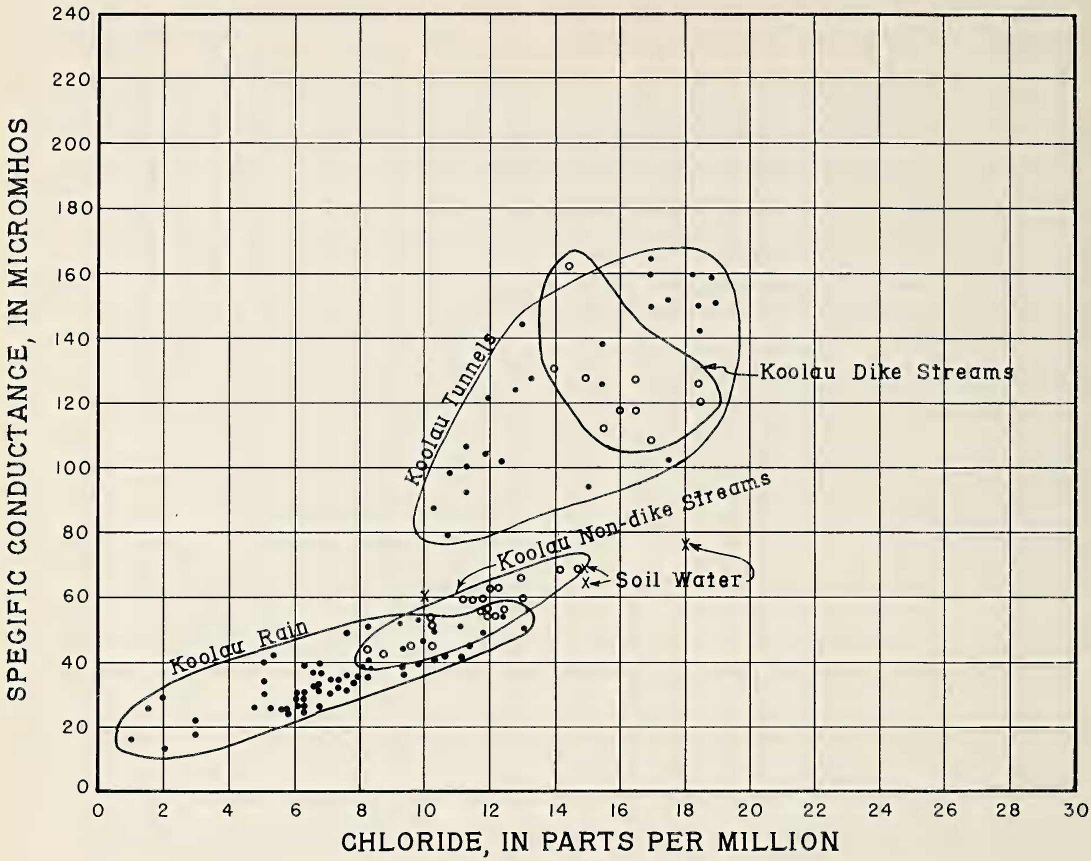

FIG. 3. Specific conductance-chloride relationship for various types of mountain water.

ably because the increase in terrace area downstream provides a concomitant increase in water stored in the soil. However, after periods of low rainfall, the flow decreases progressively in the downstream direction, because storage in the alluvial terrace is at a minimum and loss through the stream bed exceeds replenishment from the terrace deposits.

RAINFALL-RUNOFF RELATIONSHIPS

An appreciable amount of data relating rainfall and runoff has been reviewed in the literature but most of it refers to areas with temperate climates. Langbein et al. (1949) summarized annual runoff in the United States and related rainfall and runoff for selected drainage basins throughout the country. Similar data of a general nature are included in a study by Langbein and Schumm (1958) relating sediment yield to mean annual precipitation. In these works the maximum rainfalls considered are approximately 60 inches per year, which in the Temperate Zone represents a humid climate. However, the relationships suggested evidently are not applicable to the wet Koolau mountains. For instance, the extrapolation of the annual rainfall-runoff relationship given in Langbein and Schumm (1958: 1077, fig. 1), adjusted to a mean annual temperature of 70 F, which approximates conditions in the central Koolau mountains, would give a considerably higher ratio of runoff to rainfall than actually occurs in these mountains.

In Table 4 are listed rainfall and runoff quantities, and runoff as a percentage of rainfall in upper Kipapa basin for the 3 years of record, the 3-year average, and selected shorter periods.

TABLE 3

DAILY FLOW IN KIPAPA STREAM IN MILLION GALLONS PER DAY

PERIOD	MEAN	MEDIAN	PRINCIPAL MODE	MINIMUM	MAXIMUM
1957	5.6	1.1	1.5	.01	145
1958	8.2	1.4	1.5	.08	388
1959	3.2	.45	.15	approx. 0	102
1957–59	5.7	.88	1.5	approx. 0	388

The rainfall volumes were computed as outlined previously in this paper, and the runoff values were obtained from the daily stream-gage records. In cases where runoff had not returned to base flow before the end of the selected period, the proportion flowing beyond the limits of the period that was traceable to rain falling during the period was determined by using the cumulative decay curves in Figure 5. This was needed most for the isolated cyclonic storm of March 5–6, 1958. In general, however, the shorter periods were chosen so that the stream was at low flow at the beginning and at the end of the period. The rain gages were read on the first and last day of each period. Both the wettest and driest intervals between rain-gage readings for the 3 years of record are included in Table 4. The remarks column suggests the rainfall conditions in the basin relative to the normal.

The runoff expressed as a percentage of rainfall shows that on an annual basis the ratio of runoff to rainfall is much smaller than would be expected from extrapolation of the generalization determined in humid temperate climates. The ratios for the calendar years and for the 3-year average indicate that the mean annual runoff is 20 to 30% of the mean annual rainfall in the basin, although in the very dry year of 1959 only 13.6% of the rainfall was accounted for as runoff. The reduction in streamflow during dry years is proportionately greater than the reduction in rainfall.

In a very wet 26-day period of predominantly cyclonic rainfall in January, 1957, during which

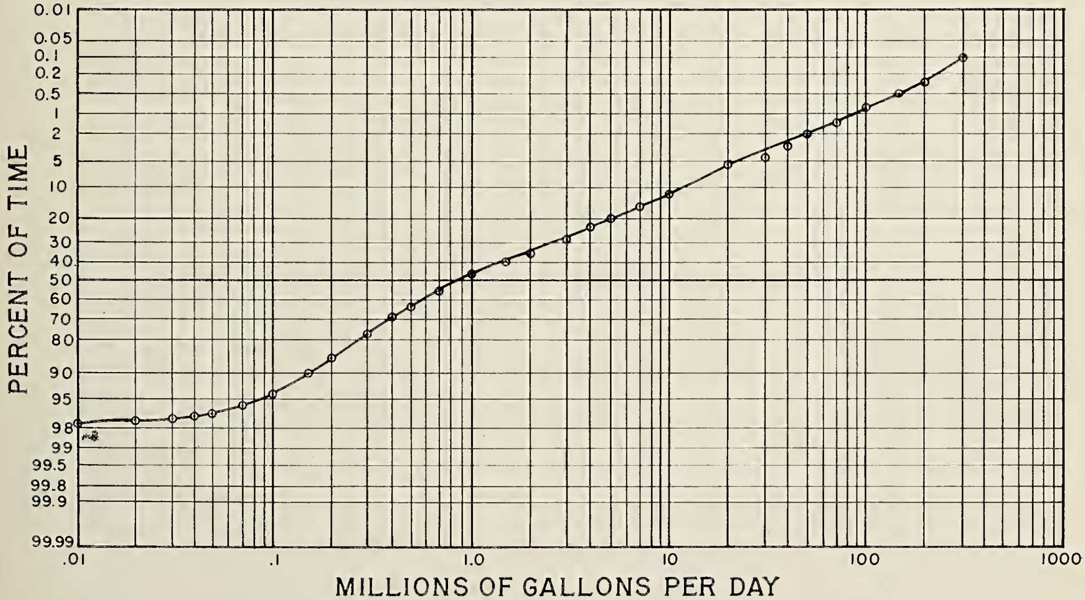

FIG. 4. Flow-duration curve of Kipapa Stream.

an average of 19.5 inches of precipitation was measured in the basin, 38.2% of the rainfall left the basin as runoff. This interval was characterized by moderate daily rains during the first 12 days, heavy daily rains during the following 12 days, and no rain during the remaining 2 days. It is likely that this period represented a nearly minimum opportunity for evapotranspiration because it occurred during a winter month when temperatures were low, the days were short, and clouds covered the basin much of the time. The runoff-rainfall ratio could be expected to approach a maximum under such conditions.

The intense cyclonic storm of March 5–6, 1958, during which an average of 14.2 inches of rain fell in the basin in a 36-hour period, resulted in a total runoff of 33.4% of the total rainfall. The runoff during the 2-day storm accounted for 89% of the total runoff from the storm, and the day following accounted for an additional 7%. The month preceding the storm was unusually dry, having produced only 2.8 inches of rain at the stream-gaging station, and the 20 days following the storm were even drier. A portion of the storm rainfall unquestionably was taken up in satisfying soil-moisture requirements because of the relatively dry antecedent conditions, but nevertheless the runoff-rainfall ratio shows that even under intense storm conditions only a moderate quantity of the rainfall leaves the basin as runoff.

During dry periods the runoff, expressed as a fraction of rainfall, decreases sharply so that in the driest extended period (February 26–April 3, 1957) in the 3-year record only 4.5% of the rainfall flowed from the basin as runoff. According to the U. S. Weather Bureau Climatological Reports, this period included the driest month of March in 10 years. On most days of this dry period the basin had only a spotty cloud cover or none at all, and gentle variable winds predominated. High evapotranspiration rates prevail under such conditions and most of the small quantity of precipitation that fell probably was consumed by vegetation or evaporated. No intense rain showers were reported during the period.

The data in Table 4 suggest that the fraction of cyclonic rainfall running off exceeds that of orographic rainfall. This is reasonable to expect because cyclonic storms normally yield high rainfall amounts that are evenly distributed throughout the basin. On the other hand, orographic rainfall is greatest in the upper portion of the basin but decreases toward the southwest in the direction of the stream-gaging station. During cyclonic storms, the stream thus picks

TABLE 4

RAINFALL-RUNOFF RELATIONS IN THE PART OF KIPAPA BASIN UPSTREAM FROM THE STREAM-GAGING STATION NEAR WAHIAWA

PERIOD	CIRCULATION PATTERN	MILLION GALLONS		RUNOFF AS % OF RAINFALL	REMARKS
		Rainfall	Runoff		
Annual					
1957	mixed	9,909	2,024	20.4	moderately dry
1958	mixed	11,798	3,002	25.4	nearly normal
1959	mixed	8,568	1,166	13.6	very dry
1957–59 (total)	mixed	30,275	6,192	20.5	dry
Short Period					
Jan 2–28, 1957	cyclonic	1,146	437	38.2	average rainfall in basin for 26-day period=19.50 inches
Mar 5–6, 1958	cyclonic	1,056	353	33.4	average rainfall in basin for 36-hour period=14.16 inches
Oct 21, 1958–Jan 6, 1959	mixed	2,642	830	31.4	wet
Mar 11–May 13, 1959	orographic	1,644	277	16.9	dry
July 29–Oct 29, 1959	mixed	2,200	311	14.0	dry
May 28–Sept 3, 1957	orographic	2,687	319	11.9	very dry
May 13–July 29, 1959	orographic	1,438	110	7.7	very dry
Feb 26–Apr 3, 1957	mixed	243	10.9	4.5	extremely dry

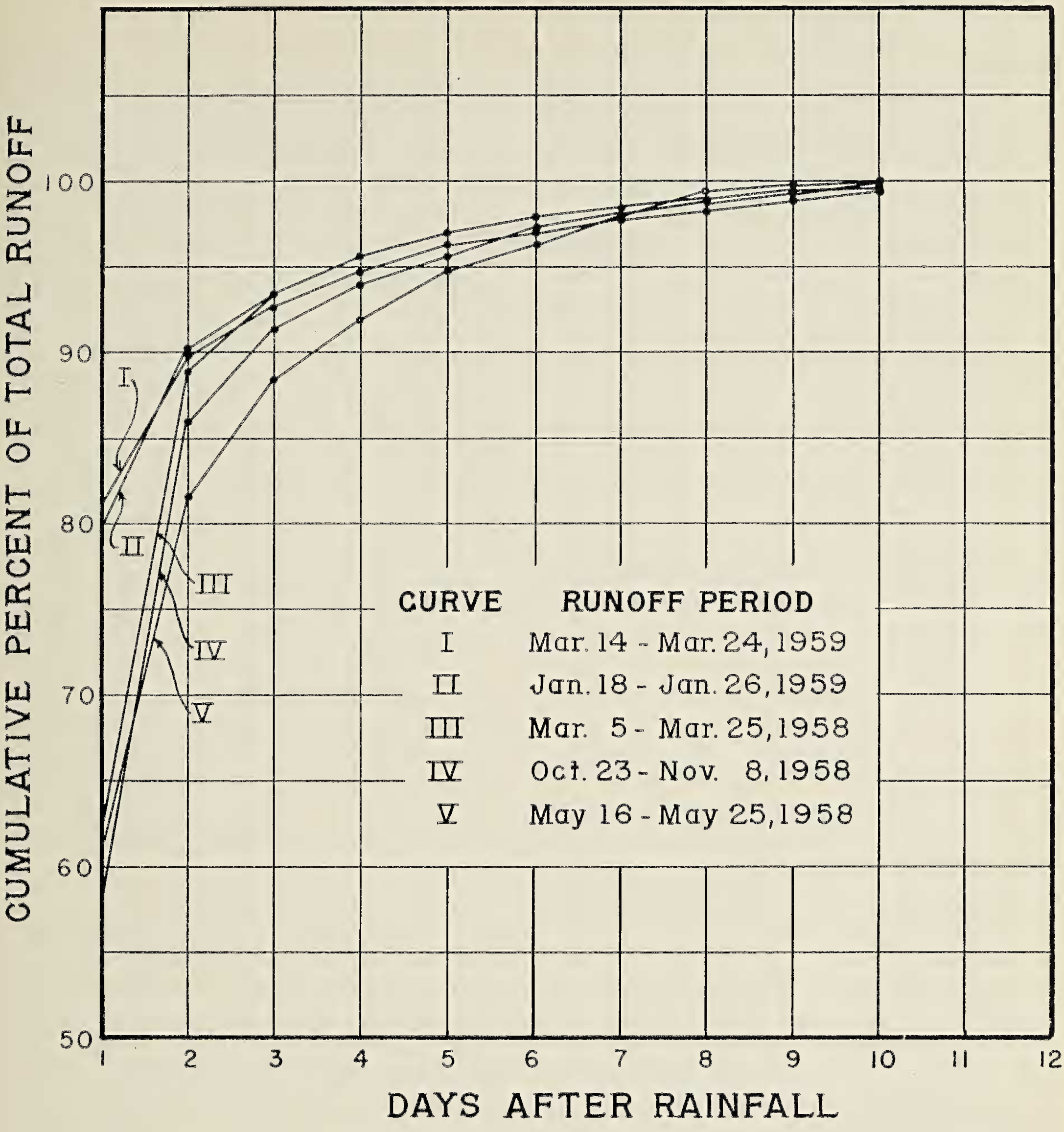

FIG. 5. Flow-decay curves for Kipapa Stream. Each curve shows the progressive reduction in stream flow following a single isolated storm.

up comparable amounts of water throughout the basin, whereas during orographic showers the water available to the stream decreases markedly leeward. The loss of flow into the stream banks and through the stream bed is therefore greater for orographic rains.

It should be reiterated that runoff-rainfall relationships explained above apply to a basin in the leeward central Koolau Range that has a mean annual rainfall of about 70 inches at its leeward terminus and 240 inches at the point of maximum fall. A change in the isohyetal dimensions of the basin would result in different runoff-rainfall characteristics. A basin having less than 70 inches of rainfall at its leeward end probably would have a smaller runoff-rainfall ratio, and a basin having more than 70 inches at the leeward end would have a higher ratio.

No long-term records are available for a basin having less rainfall at the leeward end but otherwise having similar environmental conditions as Kipapa. A direct comparison can be made, however, between Kipapa Stream and Kaukonahua Stream which drains a similar central Koolau basin but has considerably greater isohyetal dimensions. Rainfall and runoff records were obtained for many years on the part of Kaukonahua basin lying above the mean annual 220-inch isohyet. Kaukonahua is north of Kipapa in the wettest section of the leeward Koolau Range, and the part of the basin referred to lies within the 220- and 300-inch isohyets. Annual rainfall volumes were computed for this part of the Kaukonahua basin by using the rainfall curve derived from the Kipapa study. Figure 6 is a plot of the cumulative annual rainfall against cumulative annual runoff for the 17-year period between 1935 and 1951. The plot shows that in this area of very high rainfall annual runoff accounts for about 50% of the annual rainfall.

CONCLUSIONS AND ADDITIONAL REMARKS

Three years of records have shown that rainfall in the wet mountain part of Kipapa basin, which is representative of the leeward central Koolau Range, increases exponentially with distance toward the summit of the range, reaching a maximum about half a mile from the summit ridge. The empirical equations derived for this relationship are statistically reliable and permit easy calculation of the volume of precipitation that falls in the basin. The area investigated is in the wet zone where the rainfall ranges from about 70 inches at the leeward end to about 240 inches at the point of maximum fall.

Although the annual rainfall is heavy, only about ¼ leaves the basin as runoff. The remainder either infiltrates to the basal ground-water body or is consumed by evapotranspiration. The amount of infiltration was not possible to determine directly, and the measure of evapotranspiration is fraught with uncertainties. However, the geology of the basin system suggests that a large proportion of the rainfall moves down through the rocks as recharge to the basal ground-water body. The soil mantle is highly absorptive and the basalts underlying it are highly permeable.

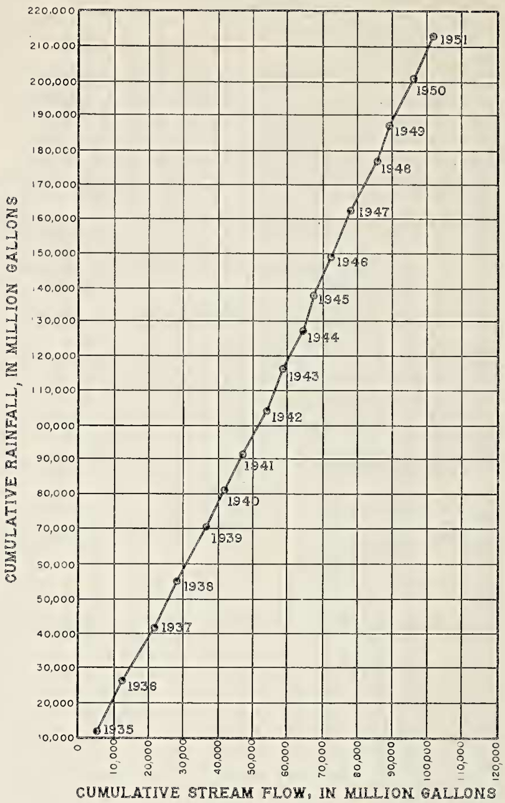

FIG. 6. Double mass curve of cumulative rainfall against cumulative stream flow for Kaukonahua Stream near Wahiawa.

The rate of evapotranspiration also could be expected to be considerable because the mean annual temperature is about 70 F and a closed montane forest covers the basin. A preliminary interpretation of evaporation data from similar wet Koolau environments suggests that in this humid area evaporation can be correlated with rainfall, decreasing as the rainfall increases. This is reasonable, because the increase in rainfall implies more cloudiness, which in turn would result in a smaller amount of solar radiation reaching the ground. The apparent relationship between rainfall and evaporation can be expressed in terms of evaporation as a function of distance toward the crest. In this relationship the equation approximates the rainfall-distance equation, except that the exponential term is in reciprocal form.

Assuming for simplicity that evapotranspiration is the equivalent of evaporation, calculations based on the evaporation-distance curve for 1957 gave the loss due to consumptive use as 30% of the rainfall. For wetter years the ratio would be less, and conversely it would be greater for drier years. A higher limit of evapotranspiration results if it is assumed that the evapotranspiration throughout the basin is the same as the potential evapotranspiration estimated for irrigated sugar cane in the leeward lowlands, or about 60 inches per year. In 1957 this would have amounted to 42% of the rainfall, which probably represents an upper limit. It is more likely that the true evapotranspiration falls somewhere between the limits determined by the two approximations. If in 1957 the evapotranspiration fell between 30 and 42% of the rainfall, and if the runoff was 20% of the rainfall (Table 4), by subtraction the infiltration was between 38 and 50% of the rainfall. The assumptions made in the preceding approximation, however, would support a value nearer to 50 than to 38% as being most reliable.

Thus, from even such a rudimentary water-budget analysis we can conclude that the wet leeward central Koolau mountains provide a highly effective environment for ground-water recharge.

SUMMARY

Rainfall and runoff data have been collected for the 3-year period, 1957–59, in the upper part of the basin of Kipapa Stream in the central Koolau Range. This part of the basin is covered entirely by a closed montane forest. The soils are highly absorptive and the underlying rocks, which consist of basalt and olivine basalt of the Koolau volcanic series, are highly permeable.

The pattern of distribution of orographic rainfall was found to correlate with distance from the crest of the range, decreasing leeward according to a geometric regression. Cyclonic storm rainfall was found to be uniformly distributed. Empirical equations for the rainfall-distance relationship were derived for the 3 calendar years and selected shorter periods, and volumes of rainfall were computed from the equations.

A gage on Kipapa Stream at approximately the mean annual 70-inch isohyet provided daily flow records. A comparison of rainfall volumes with runoff volumes for the 3 years shows that the yearly runoff accounts for about 25% of the yearly rainfall. During wet periods, the runoff may amount to nearly 40% of the rainfall, and in dry periods it can be as low as about 5%. Calculations based upon two different assumptions for evapotranspiration suggest that as high as 50% of the annual rainfall may move down as recharge to ground-water bodies.

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